

SUPERCONDUCTING DIGITAL MULTIPLEXERS FOR SENSOR ARRAYS

Alan M. Kadin^{*}, Darren K. Brock, and Deepnarayan Gupta
HYPRES, Inc., 175 Clearbrook Road, Elmsford, NY 10523, USA

ABSTRACT

Arrays of cryogenic microbolometers and other cryogenic detectors are being developed for infrared imaging. If the signal from each sensor is amplified, multiplexed, and digitized using superconducting electronics, then this data can be efficiently read out to ambient temperature with a minimum of noise and thermal load. HYPRES is developing an integrated system based on SQUID amplifiers, a high-resolution analog-to-digital converter (ADC) based on RSFQ (rapid single flux quantum) logic, and a clocked RSFQ multiplexer. The ADC and SQUIDS have already been demonstrated for other projects, so this paper will focus on new results of a digital multiplexer. Several test circuits have been fabricated using Nb Josephson technology and are about to be tested at $T = 4.2$ K, with a more complete prototype in preparation.

INTRODUCTION

Arrays of superconducting and other low-temperature detectors are widely being developed for imaging across the electromagnetic spectrum, from microwaves through gamma radiation. These include microbolometers for infrared and microcalorimeters for x-ray single-photon detection. One type of detector is the transition-edge superconducting sensor (TES)¹; another is the superconducting tunnel-junction detector (STJ)². Both require cooling to very low (sub-K) temperatures for maximum sensitivity. In this context, large numbers of leads for control and readout of the array elements are impractical, since they conduct too much heat into the cryogenic environment. One approach is to multiplex multiple sensors onto the same output lines, using a matrix of switches lying close to the sensors at low temperatures.

Furthermore, the sensor signals must be amplified and transmitted to warm electronic circuits for further signal processing. In particular, SQUID amplifiers are well matched to TES sensors, providing low noise and isolation with sufficient gain to drive room-temperature circuitry. Several groups have demonstrated approaches to multiplexing multiple SQUID amplifiers, in either the time-domain³ or the frequency domain.⁴

We have made use of SQUID amplifiers in a somewhat different mode. A SQUID in the voltage state actually produces a time-series of single-flux-quantum pulses (also known as SFQ pulses or fluxons) at a rate proportional to the voltage, as given by the Josephson voltage-frequency ratio $f = V/\Phi_0$, where $\Phi_0 = h/2e = 2.07$ mV-ps is the magnetic flux quantum. These SFQ pulses (with pulsewidth ~ 2 ps and pulse height ~ 1 mV) form the basis for a superconducting logic family known as RSFQ, for rapid-single-flux-quantum.^{5,6} The pulse rate can be counted in a binary counter, effectively providing a digital measurement of the voltage. An analog-to-digital converter (ADC) based on these principles was recently fabricated in a monolithic superconducting integrated circuit based on Nb Josephson junctions,⁷ and demonstrated in liquid helium at a temperature of 4.2 K.⁸ In the present work, we describe how a set of digital switches can adapt this ADC to become a digital time-domain multiplexer (see Fig. 1). At any given time, the switch for only one sensor is open, permitting the SFQ pulses for that sensor to pass through to the counter. By proper sequencing of the switches for the SQUIDS and triggers for the counter, a properly multiplexed digital output signal can be obtained. This will be discussed in more detail below.

There are a number of general advantages of carrying out this digitization in the cryogenic environment close to the sensors. Most important among these is noise resistance; once a signal is in digital format, it is

^{*} Contact information for A.M. Kadin: Email: kadin@hypres.com, phone (914) 592-1190.

virtually immune to the effects of low-level noise. This is also true for any subsequent amplification of the signal; unlike the case for amplification of a weak analog signal, any weak nonlinearity or added analog noise should not affect the content of a digital signal, provided that it is not above the threshold level needed to produce bit errors. Furthermore, digital signals can be easily averaged to increase resolution and reduce noise, and can be conveniently calibrated for non-ideal sensors (e.g., with gain and offset corrections). Furthermore, a system of digital signals has great flexibility in scaling to large arrays and in interfacing with general-purpose computers, for further processing of digital images.

Finally, superconducting digital electronics is notable for operating at very low power levels, typically ~ 1 mW or less for a complex digital circuit. This level is compatible with monolithic integration with cryogenic sensors, without excessive heating. Conventional semiconductor digital systems generally dissipate orders of magnitude more power, and cannot effectively be integrated close to cryogenic sensors.

DIGITAL READOUT DESIGN AND SIMULATION

The digital multiplexing scheme is shown in Fig. 1. Here the output signals from a row of sensor elements are currents, each of which is inductively coupled to a SQUID loop. Each SQUID generates a pulse sequence at a rate proportional to the SQUID voltage (which in turn is linear in the signal current). Each pulse is shaped and propagated toward an RSFQ digital switch S using a Josephson transmission line (JTL). If the switch is closed, the pulse train is coupled to the line that goes to the fluxon counter. The counter generates a binary number (with, e.g., 16 bits), which can be serialized in a parallel-to-serial converter (PSC) so as to reduce the number of output leads. In practice, this is followed by a high-voltage output driver consisting of a series array of SQUIDs, so as to raise the voltage (and increase the pulsewidth) to levels more appropriate for access by standard room-temperature electronics. The layout of a 5-mm x 5mm

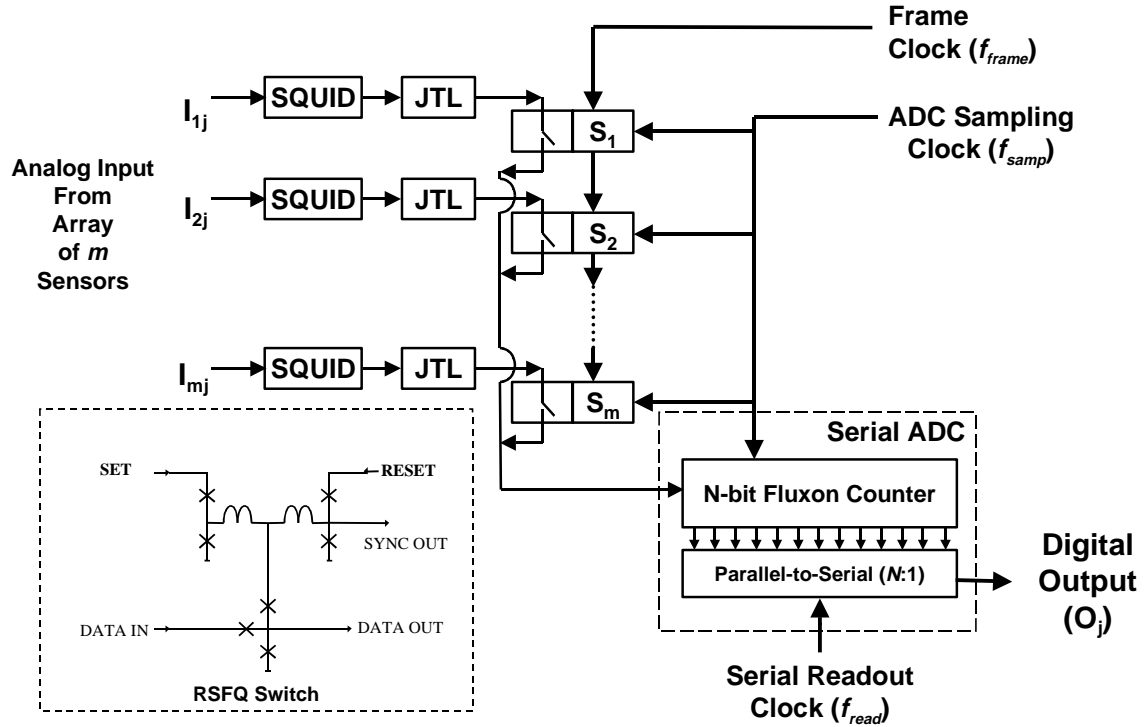


Figure 1: Superconducting digital multiplexing scheme for readout from array of TES sensors. Each SQUID amplifier generates a sequence of SFQ pulses at a rate which is linear with the sensor current. All of the switches S are initially closed, but are opened one-at-a-time to permit the pulse sequence from a particular sensor to pass through to the fluxon counter. The multi-bit binary output from the counter is periodically serialized and read out to room-temperature electronics. The inset in the bottom left shows the detailed circuit diagram of the digital switches, where \times represents a Josephson junction.

superconducting integrated circuit with these components (but only a single switch) is shown in Fig. 2a (left). The chip on the right is an array of 3 switches configured for testing of proper timing sequences. These chips are currently being fabricated by HYPRES in Nb Josephson technology based on junctions with a critical current density $J_c = 1 \text{ kA/cm}^2$ and 3- μm linewidths, and will be tested soon at 4 K.

Several clock signals are needed to synchronize the proper operation of this system. The sampling clock opens all switches and resets the counter, transferring the contents to the PSC for subsequent readout. The frame clock closes one switch, moving sequentially down the column after each sampling period. The serial readout clock reads out the contents of the PSC, so that the counter can then be reset to zero. A circuit simulation that illustrates the operation of these switches is shown in Fig. 3, for three input signals, at three different pulse rates. The switches and counters have been found in simulation to operate with acceptable margins up to pulse rates of at least 30 GHz.

DISCUSSION AND CONCLUSIONS

Let us project a digital multiplexer such as we have described as the readout electronics for a sensor array. Consider, for example, an array of 100 TES sensors, each with a characteristic response time $\sim 100 \mu\text{s}$. If the integration time is $\sim 1 \mu\text{s}$ for each sensor, this corresponds to a total count of 30,000 for a 30 GHz pulse rate. This is compatible with a 16-bit counter, which we have already demonstrated, although the system may be limited by analog noise in the sensors or input SQUIDs. With optimum layout, it should be possible to include all 100 channels on a single 1-cm x 1-cm superconducting chip. Such a chip would normally operate at $T=4.2 \text{ K}$, although it should operate equally well at the reduced temperatures typical of TES sensors. Since the total power dissipation should be less than 1 mW, it might even be possible to fabricate a complete monolithic IC that incorporates both the microbolometer focal plane array and the readout electronics.

In conclusion, we have designed and laid out preliminary superconducting circuits for a combined digitizer-multiplexer for an array of sensors such as TES microbolometers, which will be tested in the near future.

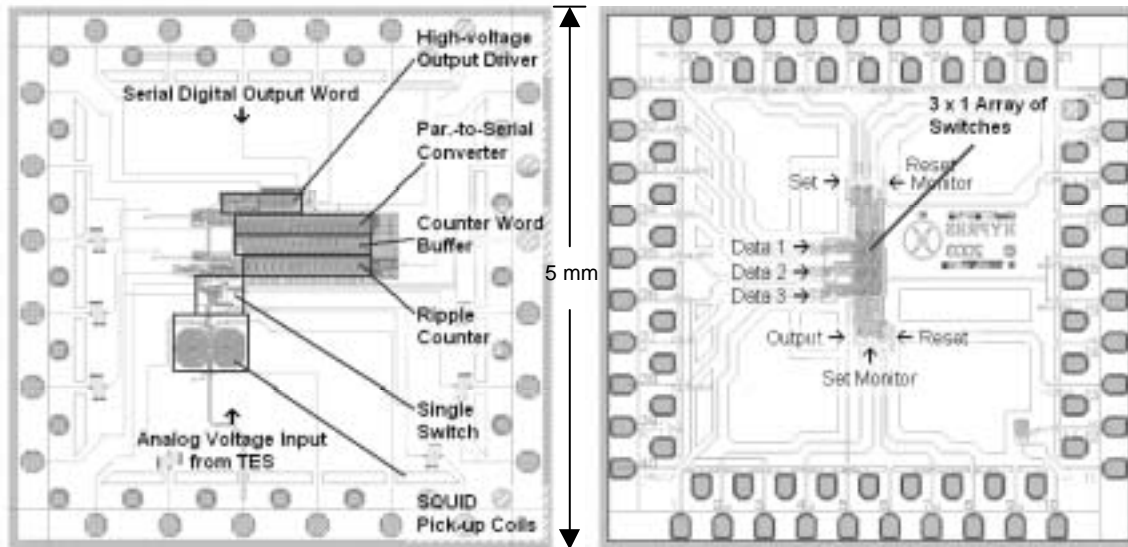


Figure 2: Circuit layouts for two superconducting Nb test chips, each 5 mm x 5 mm. (a - left) Serial ADC, with single inductive input to SQUID pickup coils, followed by a digital counter and parallel-to-serial converter and SQUID array output driver for sending digital data to room temperature. (b - right) Multiplexer test chip, with array of 3 RSFQ switches permitting sequential streaming of three independent data inputs. Following testing and analysis at 4 K, a complete digital multiplexing chip with perhaps 16 input channels and a serial ADC will be designed and tested with simulated sensor data.

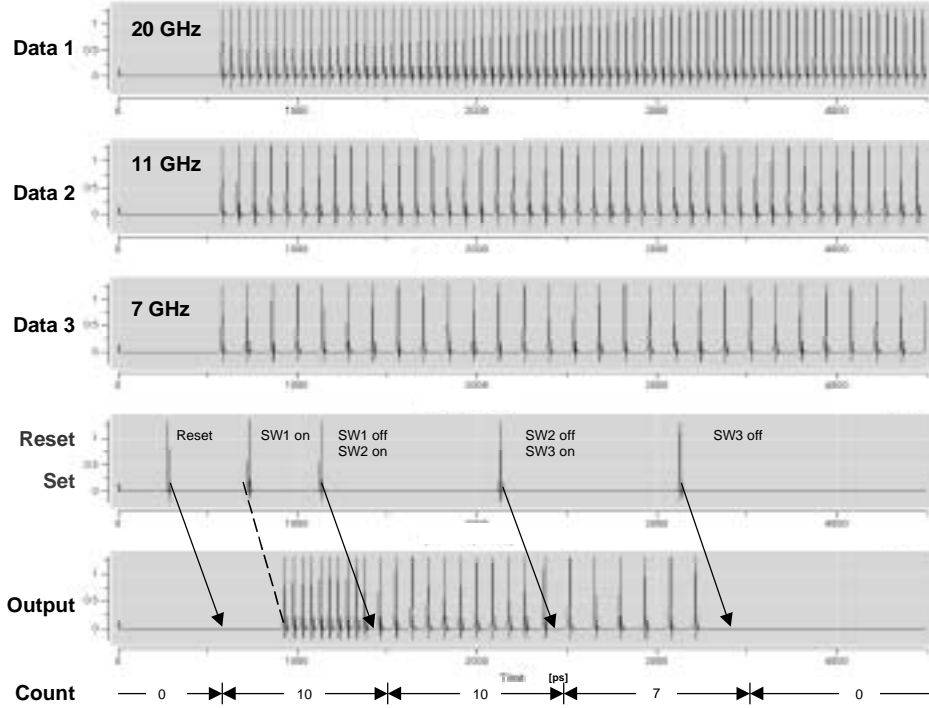


Figure 3: Circuit-level simulation of switching circuit in Fig. 2b. The 3 inputs with different pulse stream rates represent three different sensor signals. The output starts with all switches open, followed by switches 1, 2, and 3 being closed in sequence, one-at-a-time.

Digitizing the signal in the cryogenic environment offers significant advantages in terms of reduced noise and increased flexibility, particularly as the arrays become larger. Pending availability of future funding, we intend to continue toward the development of a complete integrated prototype system that generates a serialized digital output for an array of up to 100 sensors. Full integration of the readout electronics with the sensors themselves may also be feasible.

ACKNOWLEDGMENT

Research supported in part by NASA Small Business Research Project #NAS3-03044, managed by Jet Propulsion Laboratory.

REFERENCES

1. S. Deiker, J. Chervenak, G.C. Hilton, K.D. Irwin, J.M. Martinis, S. Nam, and D.A. Wollman, *Transition Edge Sensor Development*, IEEE Trans. Appl. Supercond. 11, 469, 2001.
2. P. Verhoeve, N. Rando, A. Peacock, D. Martin, and R. den Hartog, *Superconducting tunnel junctions as photon-counting imaging spectrometers from optical to the x-ray band*, Opt. Eng. 41, 1170, 2002.
3. K.D. Irwin, *SQUID multiplexers for transition-edge sensors*, Physica C 368, 203, 2002.
4. J. Yoon, J. Clarke, J.M. Gildenmeister, A.T. Lee, M.J. Myers, P.L. Richards, and J.T. Skidmore, *Single SQUID multiplexer for arrays of low-temperature sensors*, Appl. Phys. Lett. 78, 371, 2001.
5. K.K. Likharev and V.K. Semenov, *RSFQ Logic Family: A New Josephson Technology for Sub-THz Digital Systems*, IEEE Trans. Appl. Supercond. 1, 3, 1991.
6. D.K. Brock, *RSFQ Technology: Circuits & Systems*, Int. J. High Speed Electron. Syst. 11, 307, 2001.
7. M. Radparvar, *Superconducting Nb and NbN processes for medium-scale integration processes*, Cryogenics 35, 535, 1995; see also HYPRES Nb foundry design rules at <http://www.hypres.com>.
8. S. Sarwana, D. Gupta, A.F. Kirichenko, et al., *High-sensitivity, high-resolution dual-function signal and time digitizer*, Appl. Phys. Lett. 80, 2023, 2002.